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Innovative soil conditioners and mulches for forest restoration in semiarid conditions in northeast Spain

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Abstract

Restoring degraded ecosystems is a global challenge. Wherever applicable, forest restoration is one of the most effective tools for reversing degradation processes and enhancing multiple ecosystem services. In Mediterranean semiarid conditions the main limiting factor for tree establishment is the low and irregular precipitation regime, which has a particularly harmful effect in areas where the soil has a poor water retention capacity. We tested, alone and combined, two types of cost-effective and locally applied plantation techniques that aim to promote early seedling establishment: i) various mulches including biodegradable and reusable prototypes and commercial models; ii) two soil conditioners with water-superabsorbing polymers in their formulation, one of which includes a new polyacrylamide-free polymer, which was tested at various doses. In a three-year study we examined their effects on *Pinus halepensis* performance (survival, shoot and root growth and tree water status) and on soil moisture on a north-facing and a south-facing slope in Mequinenza, NE Spain. The use of mulches led to slight increases in seedling growth and soil moisture compared to untreated seedlings, without great differences between the models tested. Therefore the new prototypes can be considered as suitable alternatives to commercially available ones. On the other hand, the new soil conditioner led to much clearer positive effects. Compared to untreated seedlings, the new soil conditioner improved seedling survival, root and shoot growth and water status, as well as soil moisture. The benefits of the new soil conditioner were highest when applied at doses of 40 or 80 g per seedling. We found that this new formulation achieved similar performance as the commercially available one. Combining mulches and soil conditioners resulted in additive outcomes, rather than

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in synergistic ones. We conclude that in conditions limited by low precipitation and coarse textured soils the use of small mulches does not seem a priority technique, in contrast with the application of soil conditioners, which seems an effective option for enhancing early seedling performance.

Keywords: afforestation; Mediterranean; *Pinus halepensis*; reforestation; water-absorbing polymer

Abbreviations: RWC = Relative water content; SAP = Super-absorbing polymers; SCwSAP = Soil conditioner with super-absorbing polymers

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1. Introduction

Land degradation affects more than 2 billion hectares worldwide (Potapov et al. 2011), with a range of drivers varying among regions. In the Mediterranean basin land has been overexploited for millennia (Blondel and Aronson 1999), which has involved massive land use changes for promoting agriculture and grazing in areas recurrently affected by wildfires (Shakesby, 2011). This has put many areas under threat of erosion and desertification. In these conditions, and particularly in the semiarid areas, the spontaneous recovery of the forest cover is limited by the slow growth dynamics linked to irregular and low water availability and high evapotranspiration rates (Vallejo et al. 2012). These conditions are expected to worsen in the coming decades due to the forecasted rise in temperatures and heat waves and the decrease in precipitation in this area (IPCC, 2014). The spontaneous recovery of these areas is severely limited due to the cumulative effects of drought, wildfires and soil erosion and will strongly depend on weather and site conditions such as soil features, slope steepness and aspect (Alrababah et al. 2007).

At present, there is a wide range of eco-technological tools used to restore semiarid environments that make it possible to improve (micro)site conditions, resource availability and the capacity of plants to endure stress (Cortina et al. 2011), particularly during their first years (Vallejo et al. 2012).

One of these tools are soil conditioners, i.e. products mixed with the soil in the planting pit to improve the soil chemical and/or physical properties at micro-site level for improving early seedling performance (Coello and Piqué, 2016). The application dosage has a major effect on the cost and the performance of this technique (Del Campo et al.

2011) and therefore it should be tuned up to balance its cost-effectiveness. One of the most successful components of soil conditioners are water superabsorbent polymers (SAP), also referred to as hydrogels or superabsorbers, synthetic compounds that can absorb up to 400 times their weight in water (Rowe et al. 2005). The use of SAP – alone or combined with fertilizers and other components – has proven effective in agriculture and forestry, increasing soil water availability, reducing evaporation and enhancing early survival and growth in a wide range of species (Hüttermann et al. 2009). Most SAP are based mainly on cross-linked polyacrylamide, which is becoming less socially accepted because of the potential traces of unpolymerized acrylamide. Despite being considered environmentally compatible (Holliman et al. 2005; Hüttermann et al. 2009) and meeting the legal limits of free acrylamide, producers are developing new, polyacrylamide-free SAP (DRI, 2008); however, their optimal dosage and effectiveness in the field is yet to be established.

One limitation of soil conditioners and similar techniques in afforestation is that the improvement in site conditions often enhances competition from spontaneous vegetation, masking the potential benefits of this technique and increasing the need for weeding (Cogliastro et al. 2001, Fuentes et al. 2010). A possible solution is the use of mulches, also known as groundcovers or weeding mats, to reduce competition from unwanted vegetation. This technique involves covering the soil around the seedlings with an opaque layer that impedes weeds from germinating and becoming established near the seedling (Maggard et al. 2012). In addition to weed control, mulches regulate soil temperature and reduce soil water evaporative losses, thus increasing soil moisture (Benigno et al. 2013, Jiménez et al. 2014). They also improve soil aggregate stability and nutrient availability (Jiménez et al. 2016), which ultimately limits soil erosion. These factors have increased the interest in this single-application technique as an alternative to recurrent chemical or mechanical weeding (Coello et al. 2017). The wide range of mulch materials, colors and structures available allows fine-tuning the desired properties with regard to water and air permeability and temperature dynamics.

The most common mulching material is plastic, because of its low retail, transport and install costs (Arentoft et al. 2013). However, it has as main drawbacks its unsustainable origin, poor aesthetic value and the need to be removed at the end of its service life to avoid polluting soil and water. To tackle these limitations there is an incipient availability of biodegradable mulches in the market, made of renewable raw materials i.e. vegetal fibers and bio-based plastics (Álvarez-Chávez et al. 2012) and that do not result in a negative impact during their degradation. Another approach to enhance the sustainability of mulching is the use of waste or recycled products as raw materials, in the framework of a circular economy (European Commission, 2015). Many of these new options are at the prototype stage and require field testing to assess their potential.

The combined application of mulches and soil conditioners would make it possible to address the five priority factors proposed by Cortina et al. (2011) for field techniques that aim to improve seedling establishment: increase (i) the rootable soil volume, (ii) nutrient availability, (iii) runoff collection, (iv) water conservation and (v) control competition from extant vegetation. Although the combined application of mulches and soil conditioners with SAP (SCwSAP) seems promising, only few studies have analyzed the joint effect of these techniques on seedling performance and soil

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parameters, on broadleaved species (Navarro et al. 2005). Furthermore, SCwSAP containing polyacrylamide-free SAP have not yet been field-tested.

In this study we tested different combinations of five mulches, three of which were at the prototype stage, and various SCwSAP applications: a commercial one, containing polyacrylamide, and a new polyacrylamide-free formulation at various doses. We assessed their effectiveness in promoting early seedling performance and soil moisture in conditions limited by water shortage as a result of a semiarid climate and a poor, coarse-textured soil at two sites: a N-facing and a S-facing slope. We tested their effect on Aleppo pine (*Pinus halepensis*) seedlings, the most abundant species in semiarid conditions in the western Mediterranean (Quézel, 2000) in terms of distribution and use for afforestation purposes (Rincón et al. 2007). We hypothesized that:

i) both mulches and SCwSAP should have a positive effect on seedling performance and soil mositure, while the combined use of both techniques should lead to a synergistic performance;

ii) the performance of SCwSAP should be proportional to the application dose, which should allow determining the most cost-effective dosage;

iii) the commercial and the new SCwSAP should have a similar performance when applied at the same dose.

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2. Materials & methods

2.1. Study area and weather summary

The study area is located in Mequinenza (Aragón region, inland northeast Spain, 41.3374N; 0.1429E) and has a semiarid climate (mean annual temperature = 15.0 ºC, annual rainfall = 367 mm, Köppen classification: BS – Steppe cold). The mean altitude is 198 m o.s.l. We installed a twin trial in two nearby sites (500 m from each other): the first S-facing (aspect 210^{o}) and the second N-facing (aspect: 30^{o}), with a total area of 1.2 ha. Both plots are on steep slopes (40% and 50% inclination respectively). The soil is a Calcisol (FAO, 2015), with a sandy-loam texture, pH 7.9 and scattered gypsum veins.

During the study period, temperatures were warmer than the historical reference (Ninyerola et al. 2005). The annual precipitation was mostly in line with the reference values, although the summer precipitation varied drastically from year to year (Table 1). Daily temperature and precipitation data were obtained from the nearest weather station of the Catalan Meteorological Service, representative of the study site.

Table 1. Summary of reference (Ninyerola et al. 2005) and annual values of the main meteorological features at the study site. GS_n indicates the correlative growing season.

Year	Mean daily temperature in summer (°C)	Mean maximum daily temperature in summer (°C)	Annual precipitation (mm)	Summer precipitation (mm)	Summer precipitation events >10 mm (#)
Reference (1951-1999)	23.7	30.6	367	69	-
2014 (GS1)	24.2	31.8	370	62	2
2015 (GS2)	25.8	33.1	330	120	3
2016 (GS3)	25.0	31.9	361	11	0

The whole area was covered by Aleppo pine (*Pinus halepensis*) and had been affected by a high intensity wildfire in summer 2003. At the beginning of the experiment (2014) the area showed very poor spontaneous recovery, limited to scattered bushes of *Quercus coccifera*, *Pistacia lentiscus* and *Rosmarinus officinalis*. In the least covered areas, which were predominant in the S-facing trial, there were erosion problems including active ravines and gullies.

2.2. Experimental design

We applied the same design in the two trials: a randomized incomplete block design. Each trial consisted of six blocks, each including 75 seedlings that were randomly assigned to one of the 15 possible treatments (5 replicates per treatment per block). Treatments consisted of combinations of various mulch models and soil conditioners. In total we planted 450 seedlings (30 per treatment) in each trial. Table 2 shows the description of each technique (mulch and soil conditioner) applied.

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Table 2. Description of the experimental techniques.

Technique type	Technique code	Description
Mulch	Control	No mulch applied
	Com_Plastic	Commercial black polyethylene film, anti-UV treated, 80 µm thick.
	Com_Biofilm	Ökolys®, a commercial green biodegradable woven mat
	New_Biofilm	Prototype of black biodegradable frame (biopolymer), fused to a black commercial biodegradable film based on PHA (polyhydroxyalkanoate), 80 µm thick, manufactured by Groencreatie and DTC. The frame is to make installation easier.
	New_Jute	Prototype of biodegradable woven jute mat treated with furan bio-based resin for increased durability, manufactured by La Zeloise NV.
	New_Rubber	Prototype of black layer made of recycled rubber, anti-UV treated, 1.5 mm thick to make fixation unnecessary, manufactured by EcoRub BVBA.
Soil conditioner	SC–	No soil conditioner applied
	New_SC20; New_SC40; New_SC80	TerraCottem Arbor®, at the prototype stage when tested. Product developed for tree and shrub planting. Its formulation includes a new generation of polyacrylamide-free water absorbent polymers (36.25% of total weight), volcanic rock (48.25%), fertilizers (14.5%; NPK 3-1-7), humic acids (0.75%) and growth precursors (0.25%). 20, 40 and 80 indicate the dose applied (g seedling^{-1})
	Com_SC40	TerraCottem Universal®, a commercially available soil conditioner with cross-linked polyacrylamide and polyacrylic acid, fertilizers and volcanic rock. The dosage was 40 g seedling^{-1}

The 15 treatments were organized in three sub-experiments:

(i) Sub-experiment 1: a full factorial design combining the 6 different mulch treatments with New_SC applied at a dose of 40 g seedling^{-1} (New_SC40) or with a control (SC-). Overall there are 12 treatments with 30 seedlings per treatment, thus 360 seedlings in total. The soil conditioner dose of 40 g seedling^{-1} corresponds to the manufacturer's recommendation for the most similar commercial product available.

(ii) Sub-experiment 2: a study on the effect of four different doses of New_SC (0, 20, 40 and 80 g seedling^{-1}), combined with a reference mulch (Com_Plastic) in all cases. Each of these four treatments comprises 30 seedlings, for a total of 120 seedlings in this sub-experiment.

(iii) Sub-experiment 3: a study comparing a commercial and a new SCwSAP (Com_SC vs. New_SC), both applied at a dosage of 40 g seedling^{-1} and combined with a reference mulch (Com_Plastic). Each of the two treatments comprises 30 seedlings, for a total of 60 seedlings.

2.3. Seedling planting

In each field trial we planted 450 seedlings of Aleppo pine in early March 2014. We performed mechanical soil digging with a spider backhoe excavator in order to minimize the impact on the soil. The volume of soil stirred (not removed) was 40 x 40 x 40 cm, shaped as micro-basins to collect runoff and avoid erosion. As the land was uneven we deployed the plantation pits in random locations, with at least 3 m between two consecutive pits. We used one-year-old *Pinus halepensis* seedlings, 15-25 cm high in containers of 300 cm^3 as proposed by Puértolas et al. (2012), from the Spanish

Provenance Region 03 (*Inner Catalonia)*, which fitted the local conditions. The seedlings showed an overall good health status at the moment of planting. We applied the SCwSAP manually during planting, in sub-pits sized 30 x 30 x 30 cm, following the manufacturer's instructions: half of the dose was applied at the sub-pit bottom and the remaining half was mixed with the earth utilized to fill up the sub-pit. After planting, we installed the mulches, which were chosen with small dimensions (40 x 40 cm), aiming to adapt the costs (retail, transport, installation) to the expected poor weed competitiveness. The mulch dimensions were also similar to the area of planting pits (40 x 40 cm).

2.4. Seedling survival and growth monitoring

We monitored all seedlings to determine their survivorship (visual assessment: alive or dead), basal diameter and total height annually at the end of the first three growing seasons (Octobers 2014-2016; GS1-GS3, hereinafter). We measured basal diameter at a constant point marked on each seedling when they were planted. We conducted additional survival monitoring six weeks after planting to detect short-term dead seedlings whose failure could not be attributed to the treatment but rather to poor plant quality or an inappropriate planting operation. We removed these seedlings (21 in total) from the experiment.

2.5. Biomass allocation

At the end of the first growing season we pulled up one live seedling per treatment and block (n = 6; 90 seedlings per field trial), chosen randomly, with the root system intact, in order to study biomass allocation. We washed the root system and then divided the seedling into three components: fine roots (< 2 mm diameter), coarse roots (> 2 mm) and shoot (stem and needles). We dried the samples at 60°C for 72 h to obtain the dry mass of each component. Because we obtained similar results for fine and coarse roots in all tests, we decided to aggregate them into a single variable, root mass.

2.6. Seedling water status

We measured the needle relative water content (RWC, hereinafter) six times: July GS1 (2 measurements), August GS1, September GS1, July GS2 and August GS2. In each measurement we collected, from each trial, treatment and block (n = 6), one composite sample consisting of 15-20 needles from at least two different seedlings. Therefore in each measurement we collected 90 samples per trial, which were placed in hermetic plastic vials stored in a portable cooler immediately after collection. On the same day we measured the fresh mass of needles (FM) in the laboratory, and put them in distilled water for 18 h for full hydration. We then measured the saturated mass (SM). Finally, we dried the needles at 60^{o}C for 48 h to obtain their dry mass (DM). We calculated the needle relative water content (RWC) as: $\% RWC = 100 * (FM - DM) * (SM - DM)^{-1}$.

2.7. Soil moisture monitoring

We measured soil moisture from May to September during GS1 and GS2 (6 and 5 measurements respectively) and monthly during summer GS3, for a total of 13 measurements. Six of these dates coincided with the seedling water status measurements. We took the measurements at three constant points per treatment (n = 3; 45 sampling points per field trial) at two depths (0-20 and 20-40 cm). Sampling points

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were located 7.5-10 cm away from the seedling, and consisted on access tubes installed right after planting, through which a TDR probe (Trime-Pico T3, IMKO) was guided.

2.8. Statistical analyses

We analyzed the data independently for each trial and sub-experiment, considering treatment as fixed factor and block as random factor. In the case of RWC and soil moisture at each depth we considered the data from all the measuring dates (6 and 13, respectively) altogether in order to have a robust dataset.

For survival analyses, we built survival curves for the three first growing seasons based on Kaplan-Meier estimates (Kaplan and Meier, 1958), and we used the Mantel-Cox log-rank test to determine significant differences between treatments. We used ANOVA to assess the differences between treatments in seedling annual diameter growth and height growth (n = 30 in GS1; n = 24 in GS2-3), biomass allocation (n = 6), RWC (n = 6) and soil moisture (n = 3 for each depth). We used two-way ANOVA for sub-experiment 1 (mulch, soil conditioner, interaction mulch x soil conditioner) and one-way ANOVA for sub-experiments 2 (soil conditioner dosage) and 3 (soil conditioner formulation). We assessed pairwise differences between treatments with the post-hoc Duncan's multiple range test. Height growth, biomass allocation and soil moisture values were log or root transformed to meet the assumptions of normality and homoscedasticity, while tables and figures show untransformed data. We also calculated pairwise Pearson correlations between the measurements of RWC and soil moisture that were taken at the same day (six measuring dates), considering all treatments together. Survival analyses were run with R version 3.4.0 (R Core Team, 2017) and the survival (Therneau, 2015) and survminer (Kassambara and Kosinski, 2017) packages, while the ANOVAs were run with SPSS v19.0.

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3. Results

3.1. Seedling survival

The survival rate was high at the end of GS2 (83% in the S-facing and 86% in the N-facing trial), but dropped dramatically in GS3 (34% and 48% respectively). In the sub-experiment 1 the effect of mulches on seedling survival was not significant, with a single exception: New_Jute resulted in a significantly higher survival rate (48%) than Com_Plastic (17%), but only in the S-facing trial (Figure 1A). The use of soil conditioner had a positive effect in the N-facing trial (57% survival with New_SC40 at the end of GS3, vs. 39% for SC-), but not in the S-facing trial (Figure 1B). We found no significant interaction between mulches and soil conditioner (data not shown). In sub-experiments 2 and 3 we could not detect any significant effect of soil conditioner dosage or formulation in seedling survival (see Figures A1 and A2 in Appendix A).

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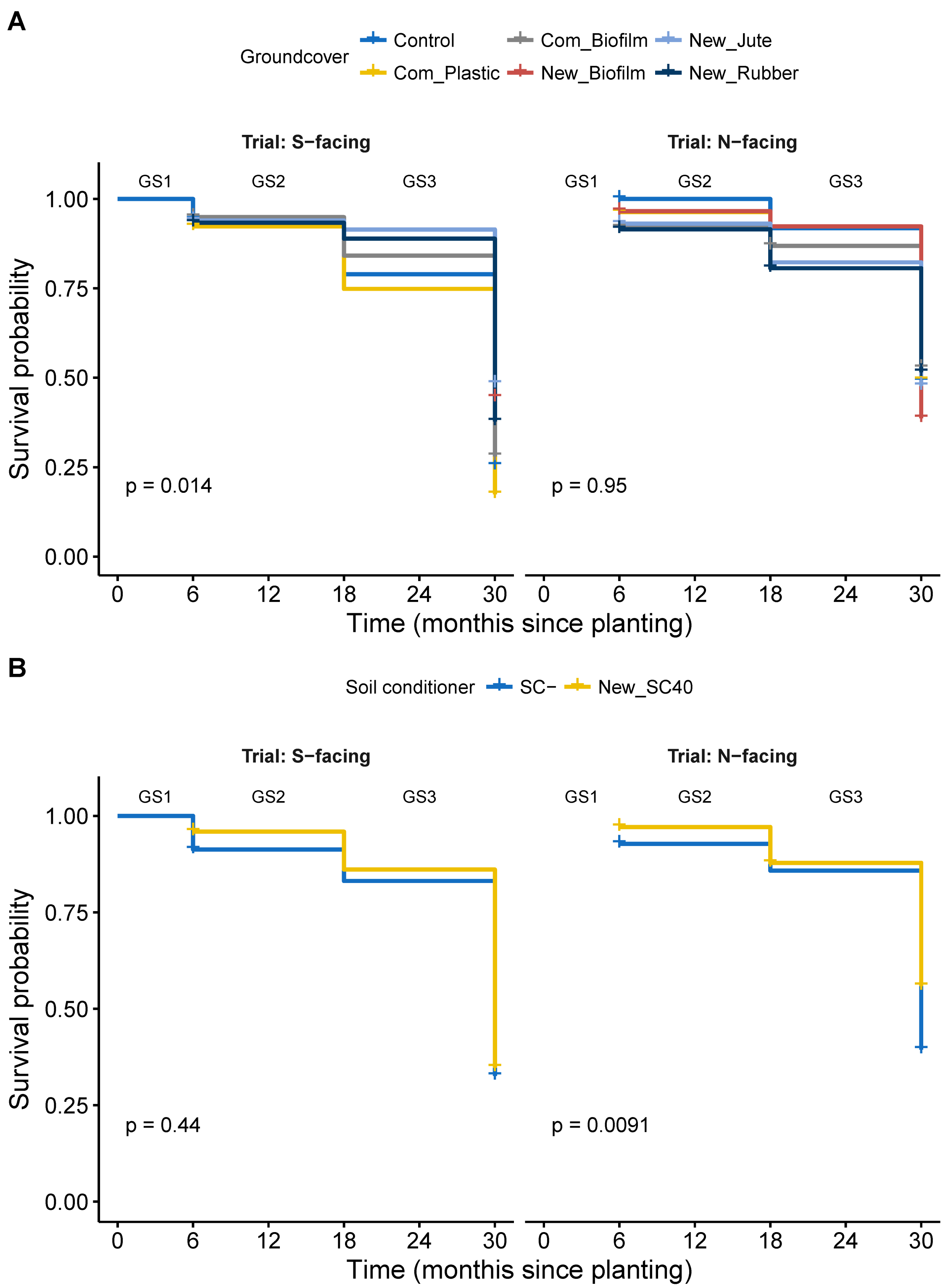

Figure 1. Survival curves based on Kaplan-Meier estimates for each field trial and factor of sub-experiment 1: combinations of (A) mulches and (B) the presence / absence of the new soil conditioner. Table 2 shows the complete description of each treatment.

3.2. Seedling growth

In sub-experiment 1 Control led to the lowest growth rates in most measurements, although the differences with mulches were not always statistically significant. In N-facing trial all mulches led to a significant increase of height growth compared to Control during GS1, while in S-facing trial all mulches except for Com_Biofilm significantly increased the diameter growth compared to Control seedlings in either GS1 and/or GS2 (Figure 2). We observed few significant differences in growth as a result of mulch models: i) New_Biofilm led to higher diameter growth than Com_Biofilm in GS1 and GS2 in S-facing trial and ii) New_Jute led to higher height growth than Com_Plastic, New_Biofilm and New_Rubber in GS1 in N-facing trial.

With regard to the use of soil conditioner, New_SC40 significantly increased (2-fold in average) seedling diameter and height growth, compared to SC- in GS1 and GS2 and in both field trials. In GS3 the positive effect of New_SC40 was noticeable in the diameter growth of N-facing trial seedlings (Figure 2).

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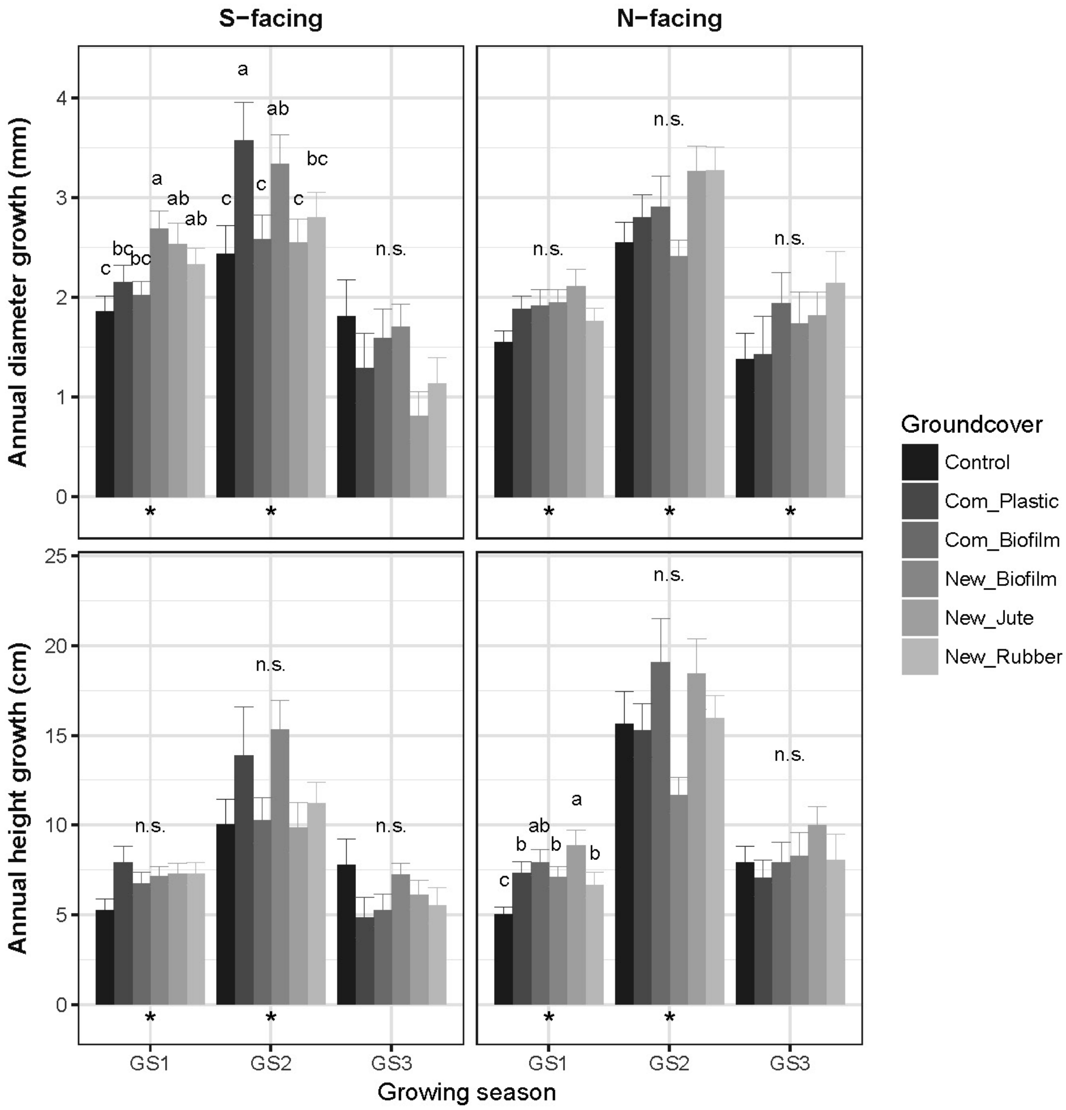

Figure 2. Diameter and height growth during the first growing seasons (GS1-GS3) for each mulch and presence of soil conditioner (sub-experiment 1), in both field trials. For each variable and year, significant differences ($p < 0.05$) between mulches are indicated by different letters (Duncan test grouping), while "n.s." indicates lack of significance. The asterisks below the bars indicate significant growth increases induced by New_SC40 compared to SC-. Table 2 shows the description of each treatment.

The addition of soil conditioner at any dose (sub-experiment 2) resulted in significant increases in growth during the first two growing seasons. In general, height growth was positively related with the dosage, although there were no significant differences in growth between the dosages 40 and 80 g seedling^{-1} (Figure 3). In some cases, the dosage 20 g seedling^{-1} did not yield significantly higher growth rates than SC-.

Both soil conditioner formulations (sub-experiment 3) led to similar growth rates (Tables B5 and B6 in Appendix B). We only found a significantly lower height growth of seedlings treated with New_SC40 compared to Com_SC40 (9.34 ± 0.84 vs. 12.67 ± 0.94; $p = 0.011$) in the N-facing trial in GS1.

Appendix B shows the outcomes of the growth data analysis for each sub-experiment.

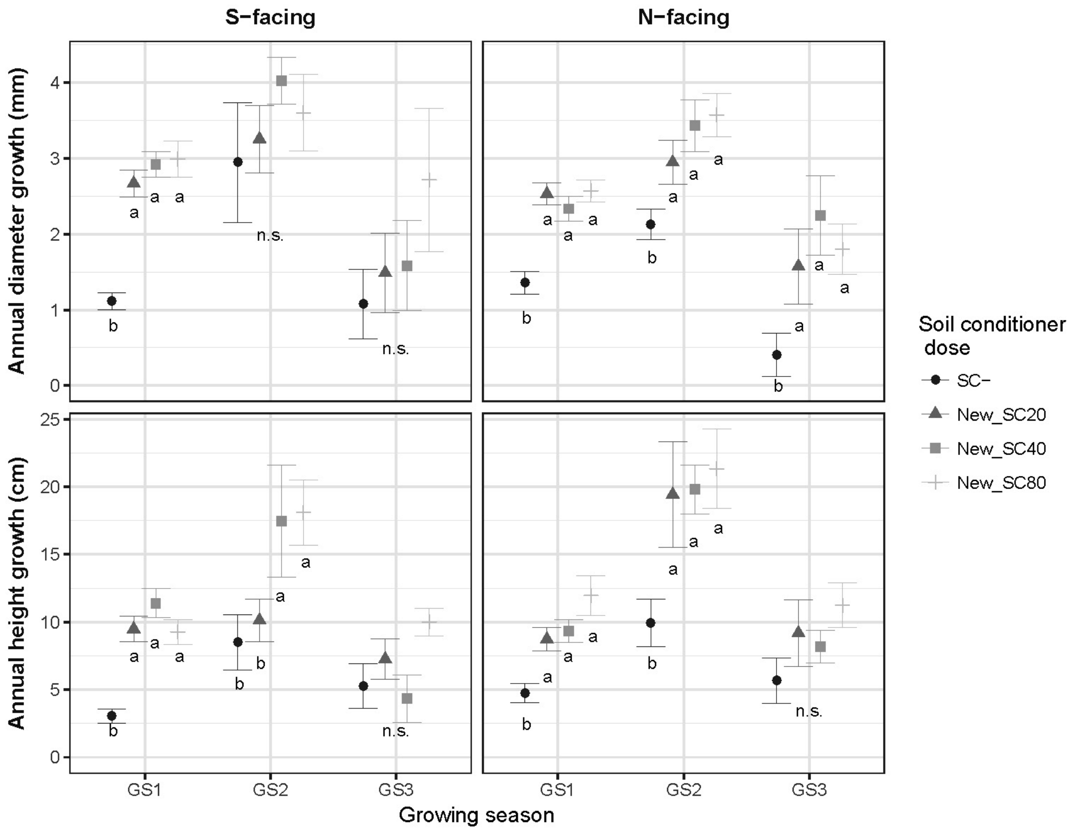

Figure 3. Diameter and height growth rates during the first three growing seasons (GS1-GS3 or 2014-2016) for each field trial and soil conditioner dose (sub-experiment 2). Error bars represent standard errors. Significant differences ($p < 0.05$) between treatments for each variable and measuring date are indicated by different letters, grouped according to the Duncan test. No significant differences between treatments is indicated by “n.s.”. Table 2 shows the complete description of each treatment.

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3.3. Biomass allocation

The results of sub-experiment 1 showed that adding soil conditioner (New_SC40) induced significant biomass gains for all fractions and in both trials (Table 3). This increase was greater for shoot mass than for root mass, leading to a significantly lower root:shoot ratio than SC- (0.43 ± 0.02 vs. 0.57 ± 0.03 in N-facing trial; 0.41 ± 0.01 vs. 0.56 ± 0.03 in S-facing trial; $p < 0.001$ in both cases). On the other hand, we did not find any significant effect of mulching or of the interaction between mulch and soil conditioner on biomass allocation (Table C1 in Appendix C).

Table 3. Biomass allocation in GS1 (2014) in the two field trials, for seedlings with (New_SC40) and without (SC-) the new soil conditioner at 40 g seedling^{-1} dose (sub-experiment 1). Value: mean ± standard error of 36 samples. Significant differences ($p < 0.05$) between treatments are indicated by asterisks.

	Root mass (g)	Shoot mass (g)	Total biomass (g)	Root:shoot ratio
S-facing trial				
SC-	1.81 ± 0.11	3.64 ± 0.35	5.45 ± 0.45	0.56 ± 0.03
New_SC40	3.38 ± 0.23*	8.75 ± 0.72*	12.1 ± 0.92*	0.41 ± 0.01*
N-facing trial				
SC-	1.55 ± 0.08	2.98 ± 0.22	4.53 ± 0.28	0.57 ± 0.03
New_SC40	2.78 ± 0.17*	6.84 ± 0.58*	9.75 ± 0.73*	0.43 ± 0.02*

Higher dosages of the new soil conditioner (sub-experiment 2) led to significant increases in root, shoot and total mass in the S-facing trial, although the effect seemed to saturate at high doses: for example, total biomass (g seedling^{-1}) averaged 3.95 ± 0.61 (SC-); 8.15 ± 1.71 (New_SC20); 14.1 ± 3.17 (New_SC40) and 14.9 ± 2.58 (New_SC80), and the difference between the two latter was not significant. The same

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pattern held true for root and shoot biomass. In the N-facing trial we found no significant differences in root, shoot or total biomass between the four dosages.

Finally, sub-experiment 3 did not lead to any significant difference between the different soil conditioner formulations on biomass allocation parameters.

Appendix C shows the outcomes of the biomass allocation analysis for each sub-experiment and field trial.

3.4. Seedling water status and soil moisture

In sub-experiment 1 we could not detect any significant effect of mulch on seedling RWC (Table D1 in Appendix D). Conversely, all mulch models led to higher soil moisture than control in N-facing trial at 20-40 cm depth ($p < 0.001$). However we did not find any significant effect at 0-20 cm depth in this trial ($p = 0.701$) nor in S-facing trial whatsoever. Using soil conditioner (New_SC40) resulted in significant increases in RWC as compared to SC- ($p = 0.010$; Table D1), and in higher soil moisture at 20-40 cm depth when considering both field trials together ($p = 0.015$).

In sub-experiment 2, although we found no difference on RWC between the three tested dosages (20, 40 and 80 g seedling^{-1}), all of them resulted in higher RWC value than SC- in both N-facing and S-facing trials ($p < 0.001$ and $p = 0.028$; Table D2 in Appendix D). However, we found no significant effect of the different soil conditioner dosages on soil moisture in any trial.

In sub-experiment 3, the new formulation resulted in a higher RWC value than the commercial one, but the difference was only significant in the S-facing trial ($p = 0.025$; see Table D3). Likewise, New_SC40 led to higher soil moisture than Com_SC40 at 20-40 cm depth (16.0 ± 0.5 vs. 14.4 ± 0.4; $p = 0.009$), but the opposite effect was observed at 0-20 cm depth (11.7 ± 0.5 vs. 13.9 ± 0.6; $p = 0.005$).

Overall we found a weak correlation between RWC and soil moisture. The r coefficients for the 0-20 cm soil depth were low, but significant: -0.36 ($p = 0.004$) for N-facing trial and -0.23 ($p = 0.012$) for S-facing trial. In the case of 20-40 cm depth the correlation was not significant in any trial ($p = 0.257$; $p = 0.843$, respectively).

Appendix D shows the outcomes of RWC analyses.

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4. Discussion

The hypotheses of sub-experiment 1 were partially corroborated: the benefits of mulching were limited to punctual improvements in seedling growth and soil moisture, while the soil conditioner had a positive effect in all seedling performance variables (survival, growth, water status) and on soil moisture. The interaction of mulches and soil conditioner was not synergetic as initially foreseen, but merely additive. The hypothesis of sub-experiment 2 was corroborated: the improvements induced by the soil conditioner were in general proportional to the application doses, although a saturating effect was detected, since we found no significant improvement of applying 80 g seedling^{-1} compared to 40 g seedling^{-1}. The hypothesis of sub-experiment 3 was also verified, with a generally similar performance of New_SC40 and Com_SC40.

4.1. Mulch performance

The five tested mulches led to slight gains in seedling growth and soil moisture, compared to control. Overall there was a 22% and 8% increase in mean diameter and height growth respectively, in line with previous works using mulches with pine species (Blanco-García et al. 2011; McConkey et al. 2012). The positive effect of mulching on soil moisture at 20-40 cm was in line with Valdecantos et al. (2009), who observed soil moisture increases under larger mulches (0.35 m^2), but in contrast with further results obtained by the same authors (Valdecantos et al. 2014), who did not observe an increase under 40 x 40 cm mulches in another semiarid site.

The lack of effect of mulching on seedling survival, biomass allocation or RWC may be due to several reasons:

(i) the low site quality limited the proliferation of extant vegetation and therefore the weeding benefits obtained by mulching. Even after three growing seasons weeds were nearly absent in the unmulched planting pits, when we had foreseen a poor, yet active weed development;

(ii) our mulches (40 x 40 cm) were rather small compared to most previous works. Available data on small mulches (60 x 60 cm or less) suggest that they result in slight gains in seedling performance and micro-site conditions (Navarro et al. 2005; Dostálek et al. 2007; Valdecantos et al. 2009, 2014), in contrast with the clearer benefits of units sized 80 x 80 cm or larger (Jiménez et al. 2014, 2016; Coello et al. 2017);

(iii) conifers often show a more limited response to weed suppression than hardwoods (Van Sambeek, 2010). Haywood (2000) and McConkey et al. (2012) even failed to detect positive effects of mulches on pine survival.

While we tested a range of mulch models with various technical, economic and environmental implications, eventually all of them led to similar effects on the variables measured, in line with Johansson et al. (2006) and Maggard et al. (2012). Among the five tested models the best overall performance could be attributed to New_Jute, which ranked first on overall seedling survival, height growth, shoot and total biomass and RWC, although the improvement compared to other mulch models was seldom statistically significant. The pale color of this model (thus not accumulating heat) and its permeability (allowing water infiltration in the case of light rainfall episodes) might have been advantages compared to alternative models in this study area subject to high temperatures and light precipitation episodes.

4.2. Soil conditioner performance

The new soil conditioner applied at 40 g seedling^{-1} (sub-experiment 1) had beneficial effects on seedling survival, growth, water status and soil moisture, compared to the control (non-application). In the N-facing trial the survival rate of seedlings with New_SC40 (almost 60%) was higher than that of control seedlings (37%), which were similar to the overall survival in the S-facing trial (35%) and to most studies in Semiarid or in low quality Mediterranean conditions with Aleppo pine: 31% (Del Campo et al. 2007a), 7-44% (Del Campo et al. 2007b) and 10-50% (Fuentes et al. 2010).

Diameter and height growth gains induced by New_SC40 compared to SC- were significant, achieving better results than field studies testing pure SAP as soil conditioner (Clemente et al. 2004; Barberà et al. 2005; Chirino et al. 2011). Compared to SC-, seedlings treated with New_SC40 had 80% higher root mass and 135% higher shoot mass during the first growing season. Contrary to our results, nursery studies with Aleppo pine show that SAPs induce larger gains in root mass than in shoot mass components (Hüttermann et al. 1999; Del Campo et al. 2011).

New_SC40 also had an overall positive effect on seedling water status and soil moisture, as observed both in field experiments (Clemente et al. 2004) and in nursery conditions (Beniwal et al. 2011; Chirino et al. 2011). The improvement in water availability induced by soil conditioners has been linked to the reduction in evaporative and percolation losses, especially in coarse-textured soils as the one in our study

(Koupai et al. 2008; Del Campo et al. 2011). This improvement may be behind the enhanced survival and growth rates observed for this treatment. However, in our trials, the presence of seedlings using available water makes it difficult to extract more definitive conclusions about the effect of treatments on soil moisture and its consequences on seedling performance. Keeping some experimental plots without seedlings (Arbona et al. 2005) and recording soil moisture on a continuous basis can shed more light on the interpretation of this variable.

Several field studies in Mediterranean conditions have observed losses of the soil conditioner effect after few growing seasons (Chirino et al. 2011; Oliveira et al. 2011). This agrees with our results: in our case, the effects almost disappeared after the second growing season, which may be due to three possible and complementary reasons:

(i) once the root system develops out of the plantation pit, the new roots grow in non-conditioned soil and cannot benefit from the effect of this technique;

(ii) the swelling capacity of SAP may decrease over time. In this regard, Holliman et al. (2005) observed this limitation after 18 months, although this figure may vary with the particular polymer/s;

(iii) the drought severity in GS3 may have transcended the new soil conditioner's capacity to help the seedling withstand the water deficit. The summer rainfall during GS3 was only 11 mm (one sixth of the historical average) and led to a dramatic decrease in overall survival rate (85% to 41%). In this regard, Del Campo et al. (2011) observed that the soil conditioner increased RWC and soil moisture under moderately dry conditions (few weeks after a rainfall), but not in severely dry ones (drought extended

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for several months). The low number of measuring dates did not allow us to draw definitive conclusions in this respect and future research should aim to detect the threshold drought intensity at which the effectiveness of a soil conditioner decreases.

4.3. Soil conditioner dosage and formulation

Increasing the dosage of the New_SC (sub-experiment 2) beyond the manufacturer's recommendation (40 g seedling^{-1}) did not result in significant improvements in plant performance. This prescribed dose of the New_SC represents 14.5 g of SAP or 0.02% in weight when applied at 30 x 30 x 30 cm soil volume, which is five times less than the SAP dosage recommended by Del Campo et al. (2011) for sandy and loamy-sandy soils.

Sub-experiment 3 showed that the new polyacrylamide-free formulation (New_SC) performed similarly to the commercial one (Com_SC) at the same dose for most variables measured and can be therefore considered as a suitable alternative. Both SCwSAPs (New_SC and Com_SC) outperformed the results obtained with pure SAP by Clemente et al. (2004), who found that 100 g seedling^{-1} dose had no effect on seedling performance. This better performance of SCwSAP compared to pure SAP at higher doses could be related to its synergistic mixture of SAP with other components (fertilizers, humic acids, root growth precursors), as suggested in nursery conditions (Vieira et al. 2005; Machado et al. 2016). Future field studies could assess the effect of each SCwSAP on seedling and soil nutrient status.

4.4. Implications for management

The new soil conditioner, especially when applied at a dose of 40 g seedling^{-1}, improved early seedling performance at a site severely limited by a low precipitation and a coarse textured soil. The main strengths of this technique, as compared to support irrigation, are cost-effectiveness, water saving during dry periods, easy application done during plantation and the lack of tending required (Coello and Piqué, 2016). It is also expected to have higher social acceptability than most commercially available soil conditioners including SAP with polyacrylamide (DRI, 2008). Nevertheless, its effect seems to be limited to a few years and to moderate drought events. Further research should help elucidate the extent of these limitations.

Compared to soil conditioners, small mulches only produced slight benefits in seedling performance, making us conclude that this should not be a priority technique in pine afforestation in semiarid conditions. Wherever mulching is a suitable technique, the three new prototypes, which are either biodegradable (New_Biofilm, New_Jute) or made of recycled waste (New_Rubber) induced very similar performance than the reference plastic mulch, making them added-value alternatives considering technical, social and environmental aspects.

Our study is the first field test for the new soil conditioner and the second one including the new mulch prototypes (see Vitone et al. 2016). However, we tested these techniques on a single tree species at only two sites, and thus caution should be taken before generalizing the conclusions to other conditions. Further research examining the single and combined effect of mulches and soil conditioners in different environmental conditions and for different plant species may help elucidate their potential as restoration tools from the technical, economic and environmental points of view.

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